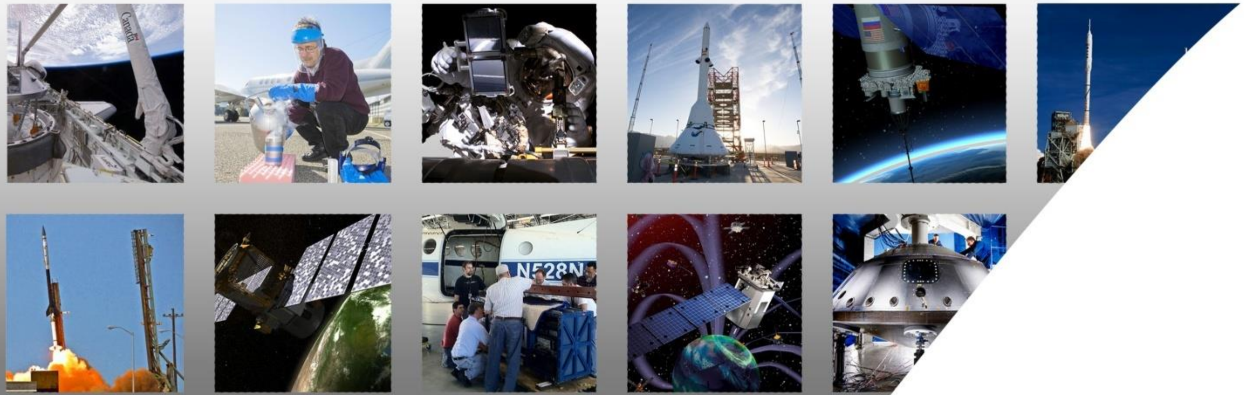


National Aeronautics and Space Administration

Testing of a 2-μm CO_2 Double-Pulse IPDA Lidar Instrument for Airborne Atmospheric Carbon Dioxide Measurement

Jirong Yu, Mulugeta Petros, Tamer F. Refaat, Ruben Remus and Upendra N. Singh

NASA Langley Research Center
Hampton, VA, USA

AGU Fall Meeting
San Francisco, CA, USA
December 15, 2015

Objective and Outline

Airborne validation of 2-μm double-pulse IPDA lidar instrument for atmospheric CO_2 measurements

- **Introduction**
  - 2-μm Double-Pulse IPDA Lidar
  - 2-μm IPDA Lidar Technique
- **Ground Testing**
  - Setup
  - Results
- **Airborne Testing**
  - Aircraft Integration
  - Plume Detection
  - Air-Sampling Validation
- **Conclusions**

Introduction: 2-μm Double-Pulse IPDA Lidar

- **Developed at NASA LaRC**
- **2-μm double-pulse laser Transmitter**
- **Wavelength control for each pulse**
- **Compact integration with receiver**
- **Small aircraft payload requirement**

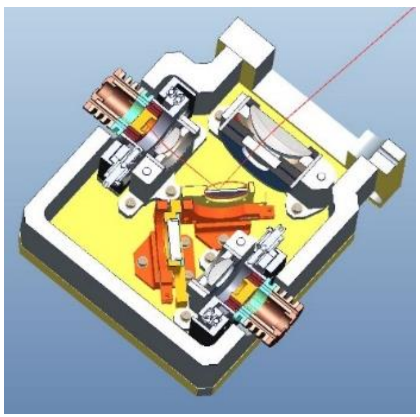
$$P(\lambda, R_A, R_G) = \eta_r \cdot \varphi_r \cdot \frac{A}{(\mathrm{R}_A - \mathrm{R}_G)^2} \cdot \frac{E(\lambda)}{t(\lambda)} \cdot \frac{\rho}{\pi} \cdot exp[-\tau(\lambda, R_A, R_G)]$$

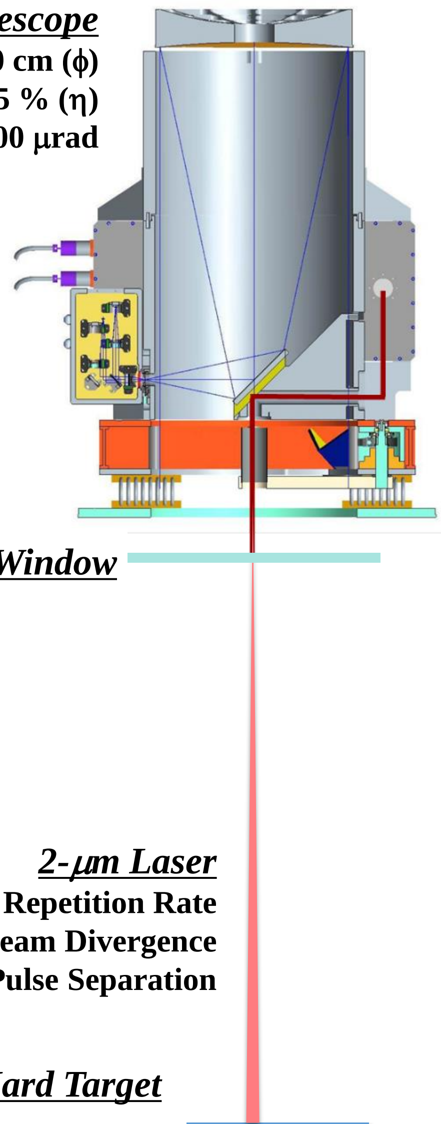
Receiver Telescope

40 cm (ϕ)
65 % (η)
300 μrad

Detector Box

2-Channels, 90/10%
InGaAs PIN (Hamamatsu; G8423-03)
TIA, (FEMTO; DHPCA-100)





Window

2-μm Laser

10 Hz, Shot Repetition Rate
150 μrad, Beam Divergence
200 μsec, Pulse Separation

Hard Target

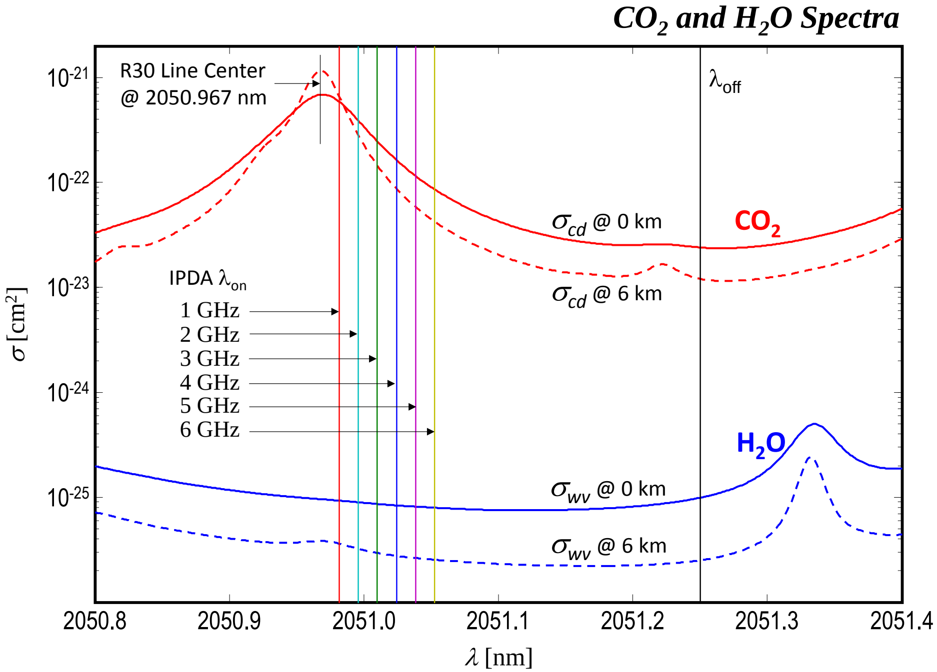
Energy Monitor

On-Line; 90 mJ, 200 nsec
Off-Line; 45 mJ, 350 nsec

Ranging

Hard Target Return

Introduction: 2-μm IPDA Lidar Technique



- **Target R30 CO_2 line**
  - **- Low temperature sensitivity**
  - **- Low molecular interference**
- **IPDA results in "inherent bias"**

$$P(\lambda, R_A, R_G) = \eta_r \cdot \varphi_r \cdot \frac{A}{(R_A - R_G)^2} \cdot \frac{E(\lambda)}{t(\lambda)} \cdot \frac{\rho}{\pi} \cdot exp[-\tau(\lambda, R_A, R_G)]$$

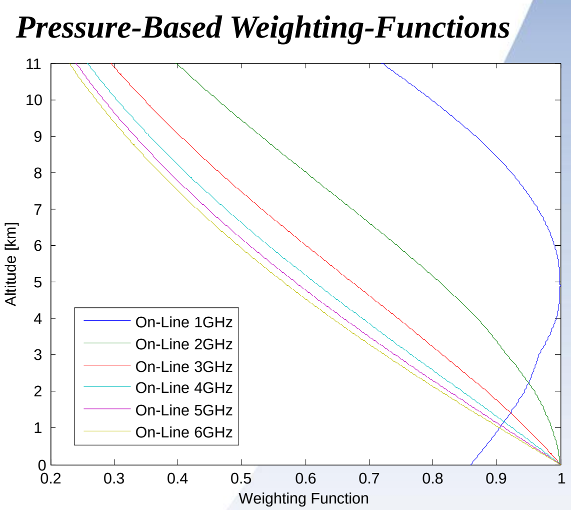
$$\Delta\tau(\lambda_{on}, \lambda_{off}) = ln\left\{\frac{P(\lambda_{off}, R_A) \cdot t(\lambda_{off})/E(\lambda_{off})}{P(\lambda_{on}, R_A) \cdot t(\lambda_{on})/E(\lambda_{on})}\right\}$$

For CO_2 Modeling

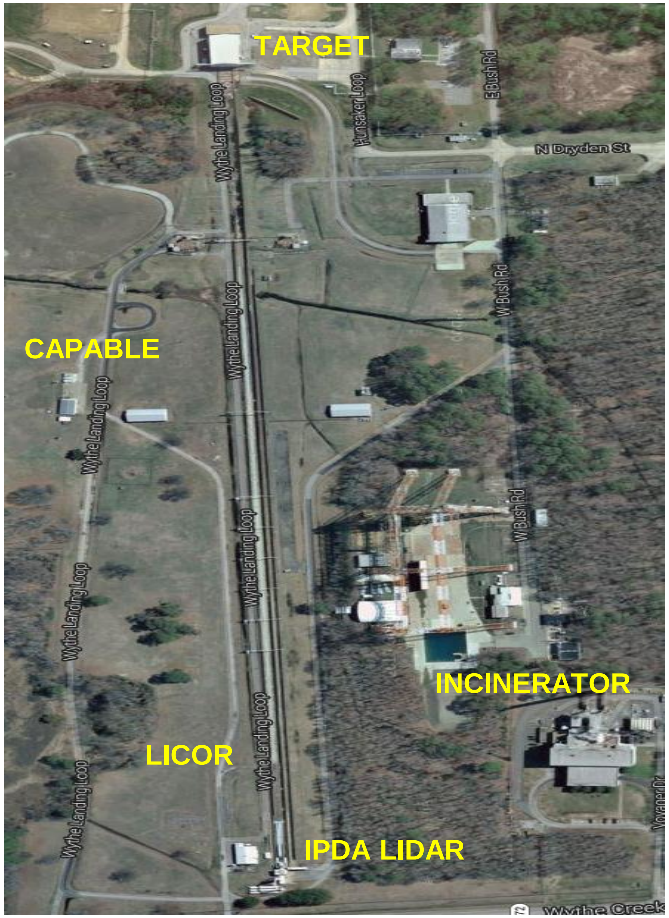
$$\Delta\tau_{cd}(\lambda_{on}, \lambda_{off}) = 2 \times 10^{-6} \cdot \int_{R_A}^{R_G} \Delta\sigma_{cd}(\lambda_{on}, \lambda_{off}, r) \cdot N_{dry}(r) \cdot x_{cd}(r) \cdot dr$$

For CO_2 Retrieval

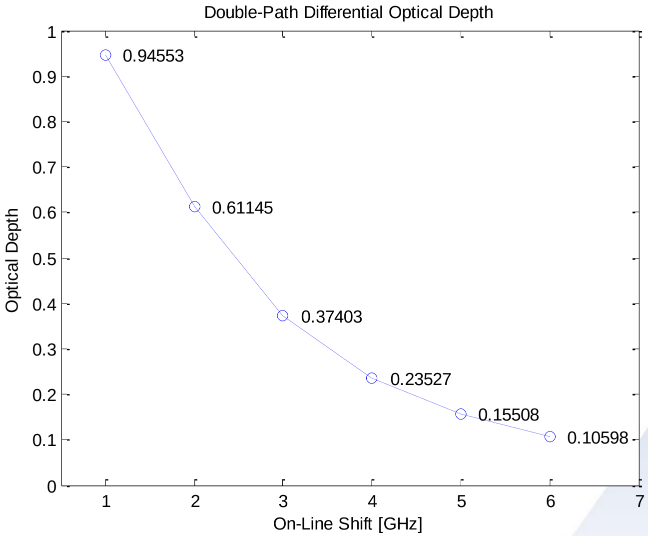
$$\Delta\tau_{cd}(\lambda_{on}, \lambda_{off}) \approx 2 \times 10^{-6} \cdot X_{cd} \cdot \int_{R_A}^{R_G} \Delta\sigma_{cd}(\lambda_{on}, \lambda_{off}, r) \cdot N_{dry}(r) \cdot dr$$



Ground Testing: Setup



- Instrument integration and ground testing conducted at NASA LaRC
- IPDA installation in a mobile trailer
- Energy monitor calibration
- IPDA alignment to calibrated hard targets
- LiCor *in-situ* sensor for CO_2 and H_2O monitoring
- CAPABLE[(1)] site for meteorological data
- Incinerator → CO_2 source

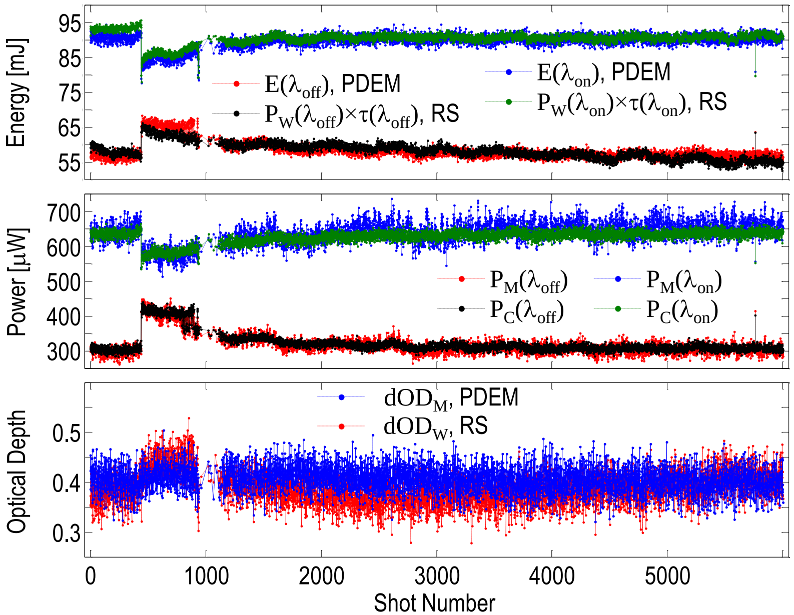


CO_2 Ground Optical Depth

(1) Chemistry and Physics Atmospheric Boundary Layer Experiment, *capable.larc.nasa.gov*

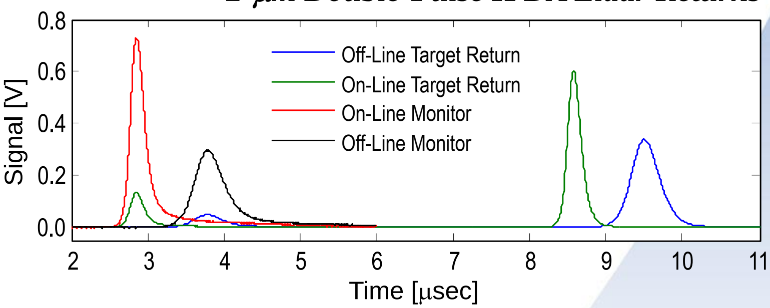
Ground Testing: Results

Detailed Record of 6000 shots (10 min) @ 3GHz & 10^3 V/A



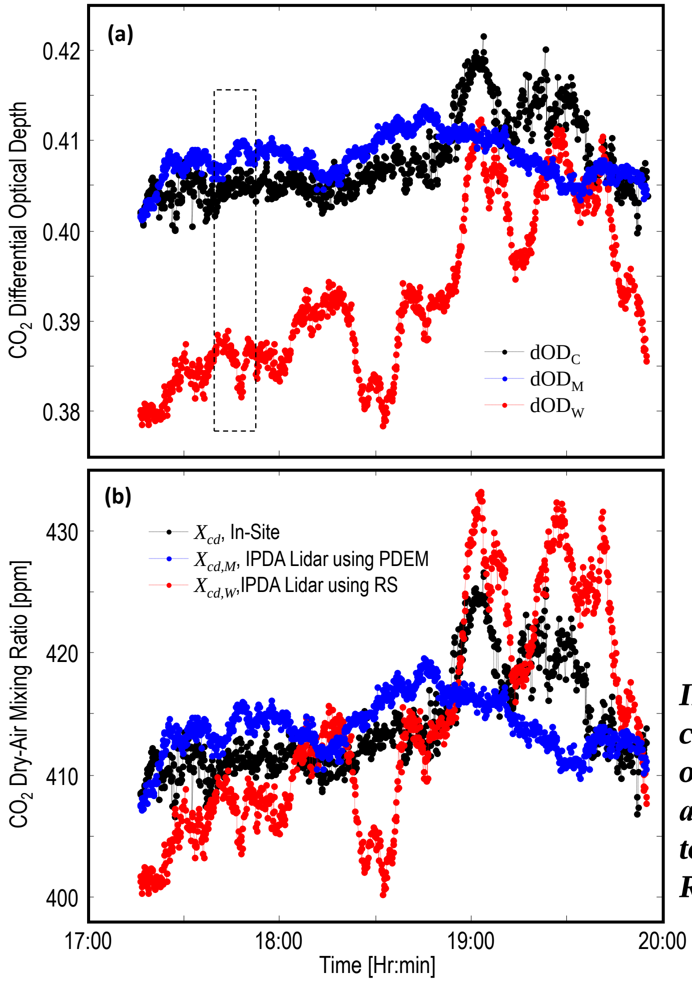
- **Per-shot analysis of return signals**
  - **- Energy monitor pulse integration**
  - **- Energy calibration**
  - **- Target return pulse integration**
  - **- Power calculation**
  - **- Optical depth measurement**
- **Alternative residual scattering investigation**
- **Per-shot analysis recovers systematic fluctuations**

2-μm Double-Pulse IPDA Lidar Returns



[(1)] **Applied Optics, 54(24), 7240, 2015**

Ground Testing: Results



IPDA lidar profile was corrected for the observed optical depth offset by adding −0.4 and 14.6 ppm to the PDEM and RS, respectively.

- **IPDA CO_2 differential optical depth measurements correlates to model**
- **Energy monitor results in lower offset**
- **Residual scattering results in better temporal profiling**
- **CO_2 differential optical depth conversion to CO_2 weighted-average column dry-air volume-mixing**
- **This validates the 2-μm double-pulse IPDA lidar for atmospheric CO_2 measurement**

Statistical Results of Differential Optical Depth and CO_2 Dry-Air Mixing Ratio Record

	dOD_C	dOD_M	dOD_W
$(\Delta\tau)$	0.4078	0.4082	0.3926
$\delta(\Delta\tau)$	0.0043	0.0023	0.0091
$\delta(\Delta\tau)/(\Delta\tau)$	1.07%	0.57%	2.31%
$\Delta(\Delta\tau)$	---	-0.0004	0.0151
$\Delta(\Delta\tau)/(\Delta\tau_C)$	---	-0.09%	3.72 %
	X_{cd}	$X_{cd,M}$	$X_{cd,W}$
(X_{cd})	414.06	414.50	399.47
$\delta(X_{cd})$	4.22 ppm	2.24 ppm	8.85 ppm
$\delta(X_{cd})/(X_{cd})$	1.02%	0.54%	2.21%
$\Delta(X_{cd})$	---	-0.43 ppm	14.59 ppm
$\Delta(X_{cd})/(X_{cd})$	---	-0.10%	3.52%

( ) is the mean value.
δ( ) is the standard deviation.
Δ( ) is the mean offset referred to the in-situ

[(1)] **Applied Optics, 54(24), 7240, 2015**

Airborne Testing: Aircraft Integration



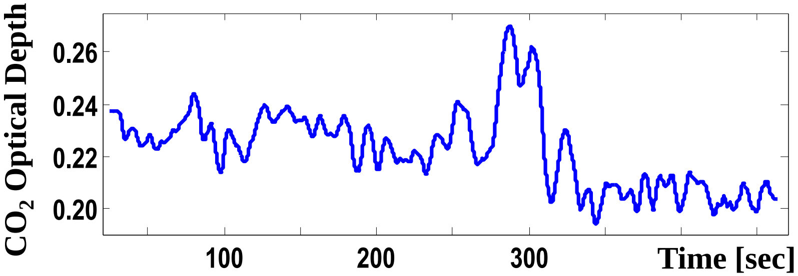

- **2-μm double-pulse IPDA integration inside NASA B-200 aircraft (Weight 500 kg, Power Consumption 2.3 kW and Size 1 m^3)**
- **Other supporting instruments includes, GPS, in-situ sensor and video recorder**
- **Airborne testing conducted through 10 flights spanning 27 hours**

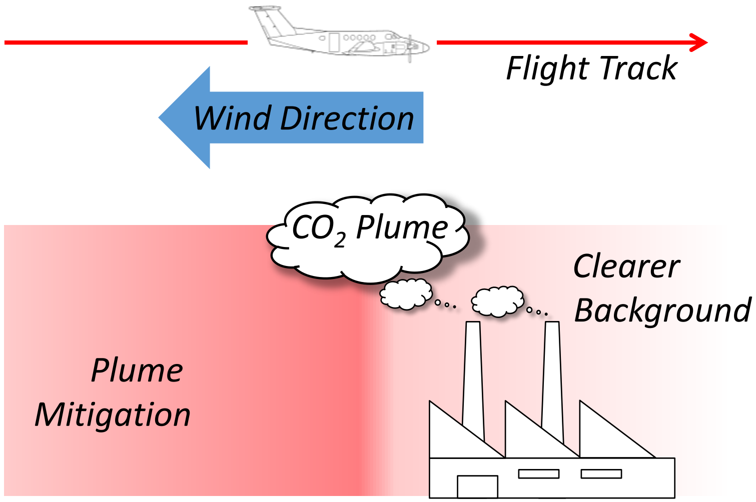
---

(1) Proc. of SPIE, 9246, 924602, 2014
(2) Proc. of SPIE, 9645, 964502, 2015

Airborne Testing: Plume Detection

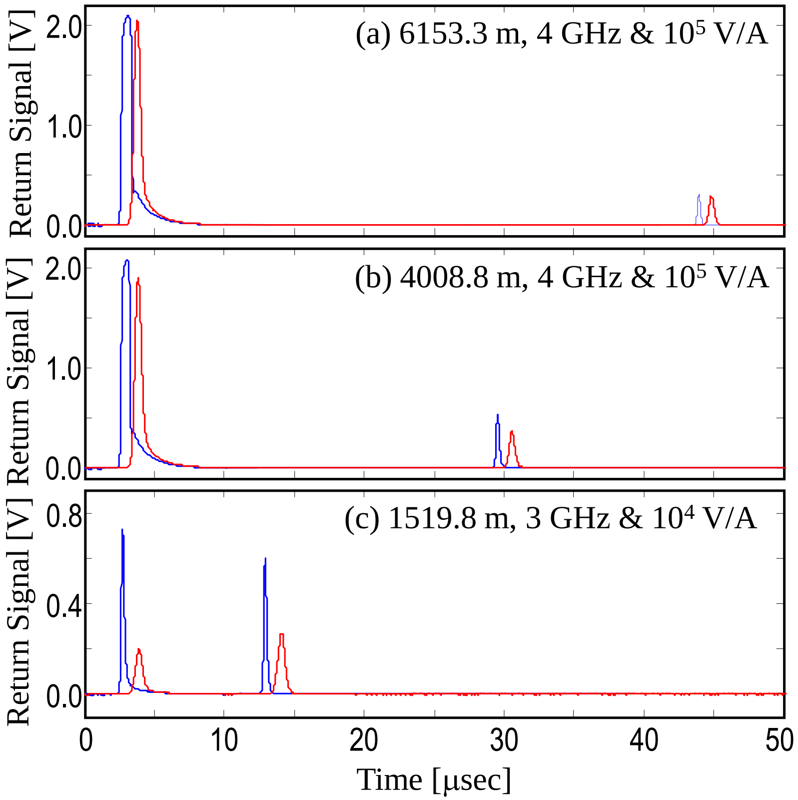
Aerial picture of Roxboro steam plant, Semora, NC. With 2 GW capacity it is one of the largest power plants in the USA



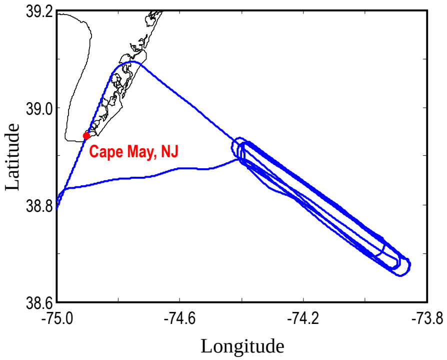


- **Coal-firing results in significant CO_2 plumes**
- **Against wind flight track above plant incinerator**
- **The 2-μm double-pulse IPDA lidar detected CO_2 differential optical depth variability**
- **9th flight; 1 km altitude & 4 GHz on-line operation**

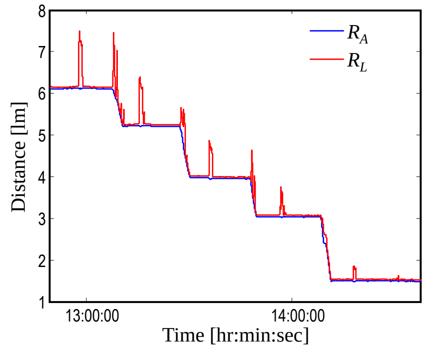
Airborne Testing: Air-Sampling Validation



Samples of On-Line and Off-Line Return Signals from Ocean Surface at Different Altitudes.



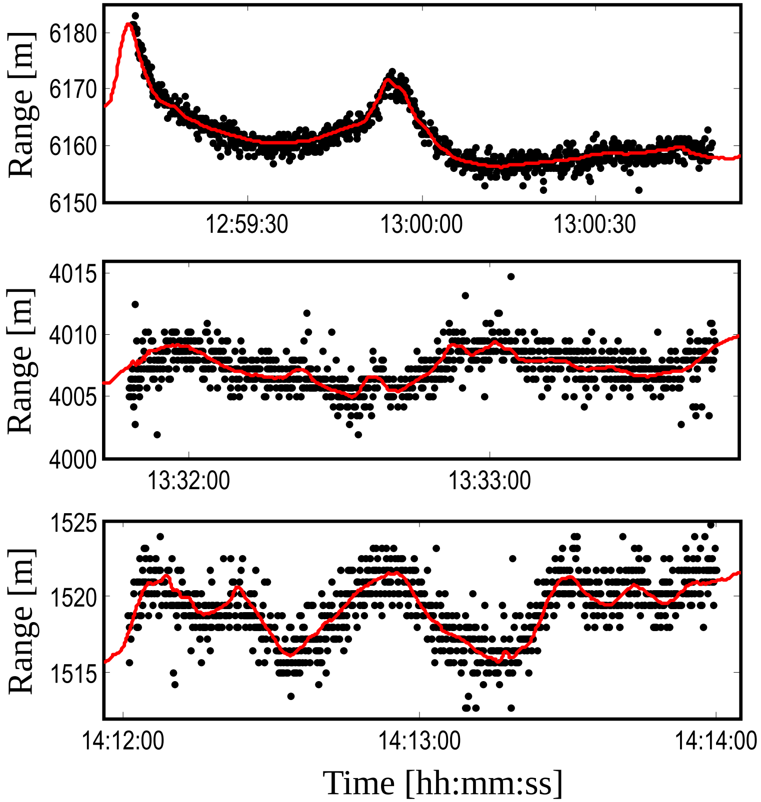
NASA B-200 Flight Track Following NOAA's Air-Sampling Flight over the Atlantic Ocean near Cape May, NJ.



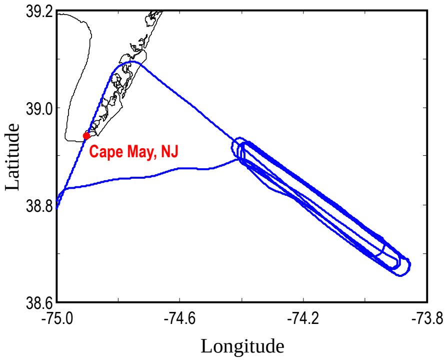
Flight Altitude Compared to the Laser-Line-of-Sight.

- **IPDA onboard NASA B-200 followed an air sampling flight conducted by NOAA at different altitude**
- **IPDA operating at 3 and 4 GHz on-line and different amplifier gain**

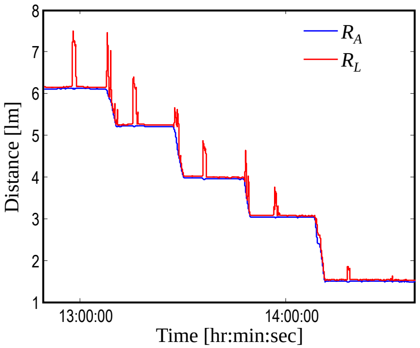
Airborne Testing: Air-Sampling Validation



IPDA Ranging (Column Length) as compared to GPS laser-line-of-Sight at Different Altitudes.



NASA B-200 Flight Track Following NOAA's Air-Sampling Flight over the Atlantic Ocean near Cape May, NJ.

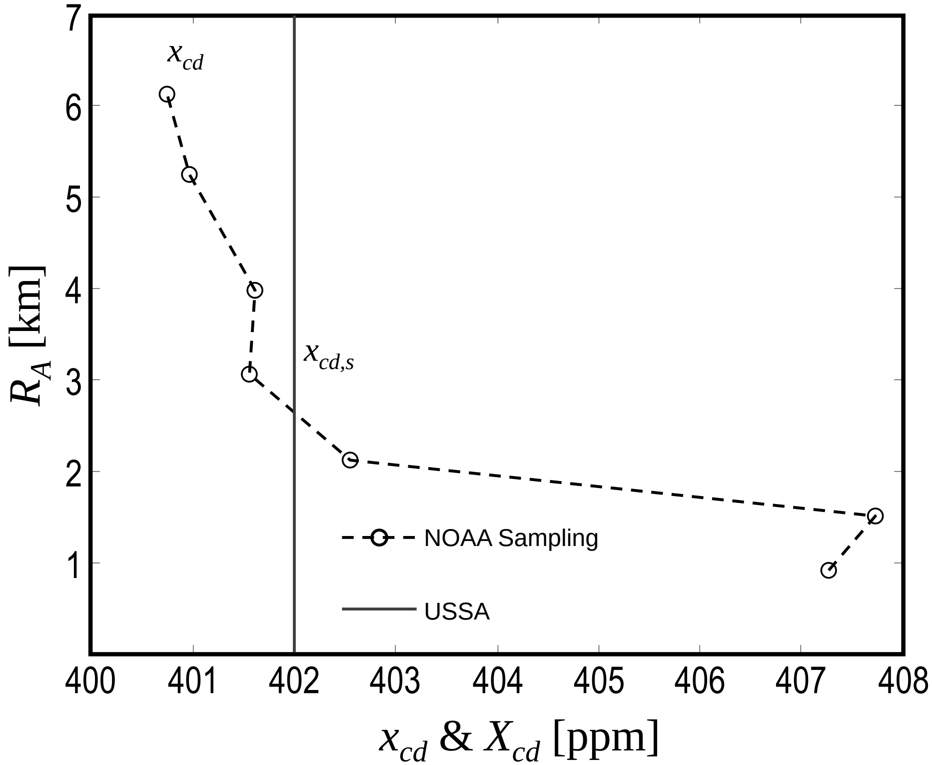


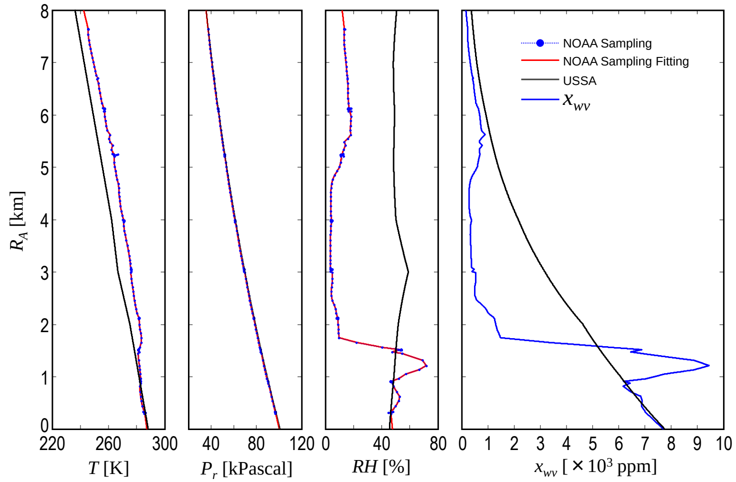
Flight Altitude Compared to the Laser-Line-of-Sight.

- **IPDA onboard NASA B-200 followed an air sampling flight conducted by NOAA at different altitude**
- **IPDA operating at 3 and 4 GHz on-line**
- **Range resolution is 0.75 m, governed by the 5 nsec sampling**

Airborne Testing: Air-Sampling Validation

CO_2 in-situ Measurement Conducted by NOAA Air Sampling. US Standard Atmospheric Model included as a reference.



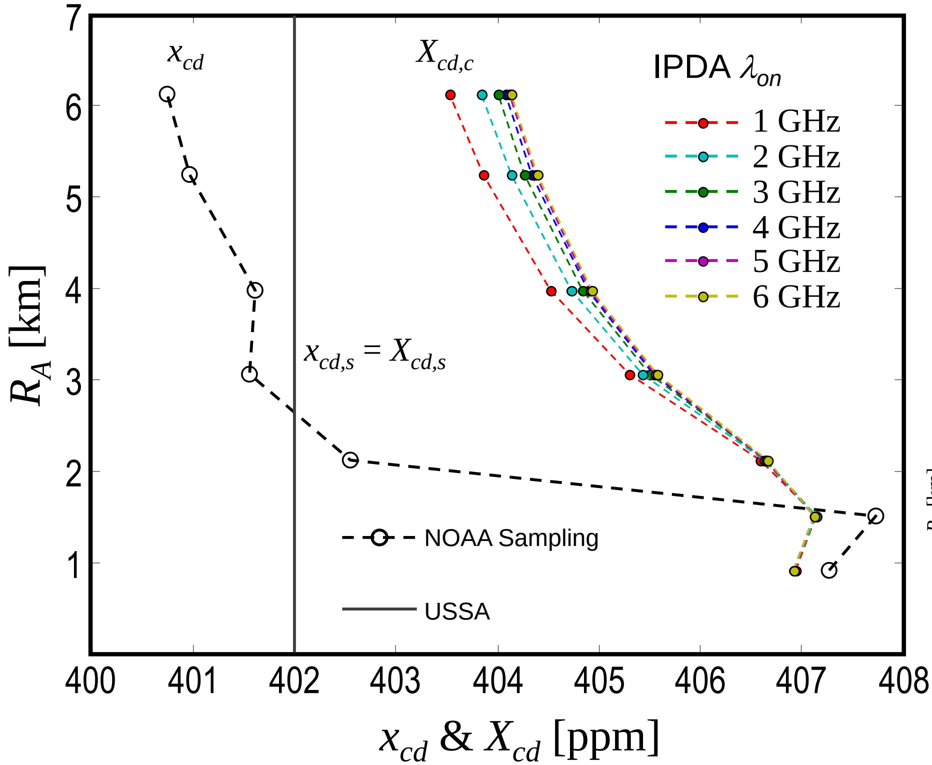


Atmospheric Temperature, Pressure and Relative Humidity Profiles provided by NOAA and Water Vapor Driven Mixing Ratio. US Standard Atmospheric Model included as a reference.

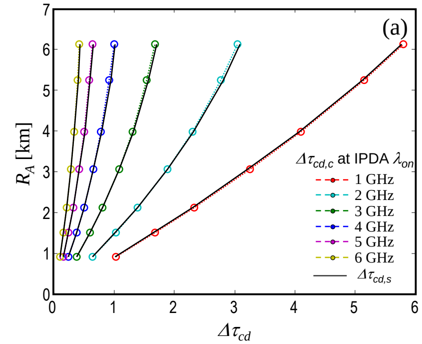
- **NOAA provides CO_2 in-situ samples and meteorological data**
- **NOAA measurements compared to US Standard Atmosphere**

Airborne Testing: Air-Sampling Validation

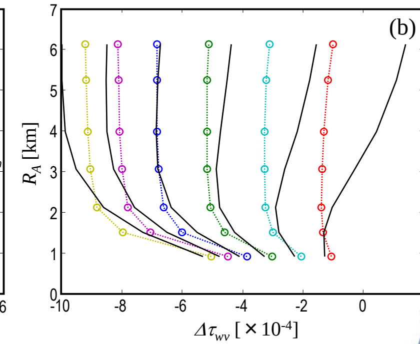
CO_2 in-situ Measurement Conducted by NOAA Air Sampling. US Standard Atmospheric Model included as a reference. IPDA Ideal Measurement.

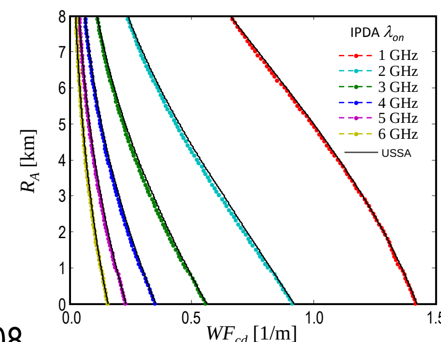


CO_2 Optical Depth



H_2O Optical Depth

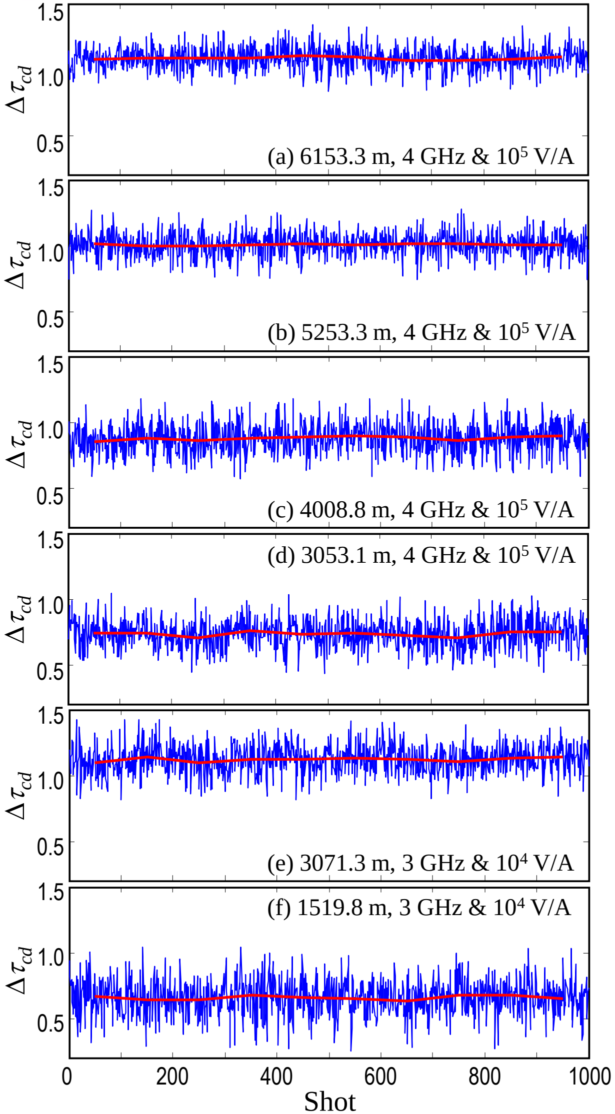




CO_2 Range-Based Weighting Function

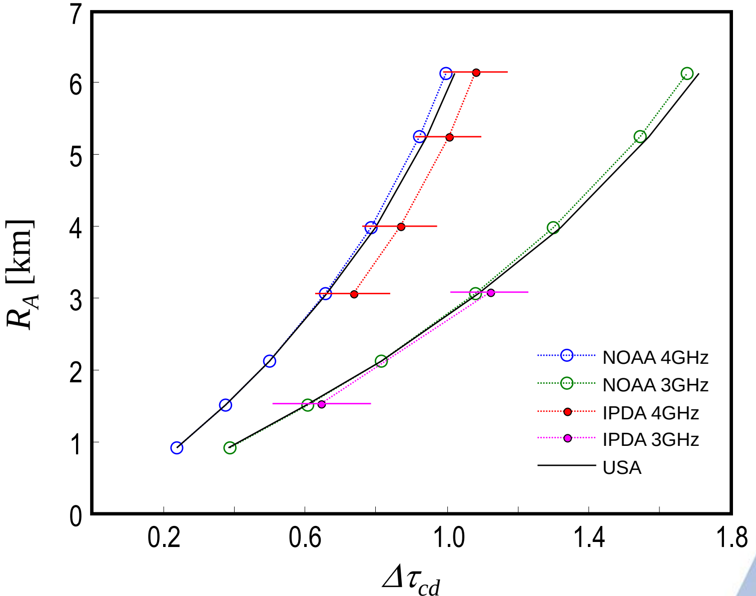
- **NOAA data applied for simulating the expected IPDA ideal measurement**
- **IPDA inherent bias wavelength and altitude dependent**
- **Insignificant water vapor biases**

Airborne Testing: Air-Sampling Validation



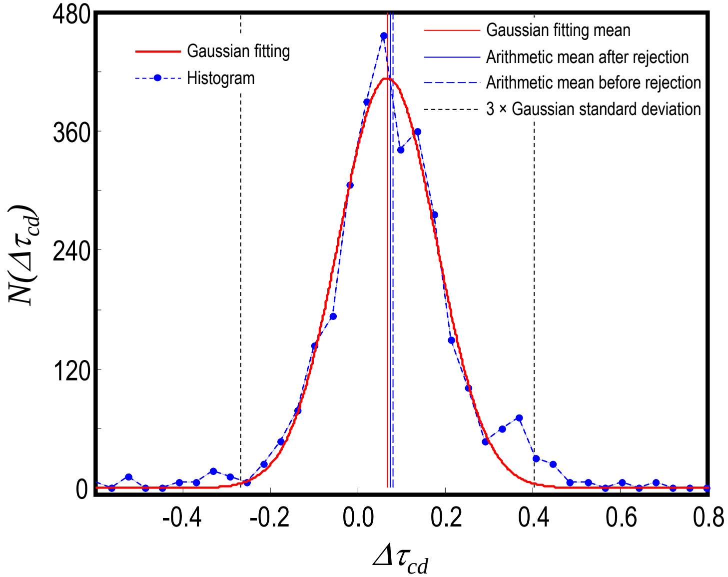
IPDA CO_2 Differential Optical Depth Measurements at Different Altitudes

CO_2 Differential Optical Depth Simulation Compared to IPDA Measurements

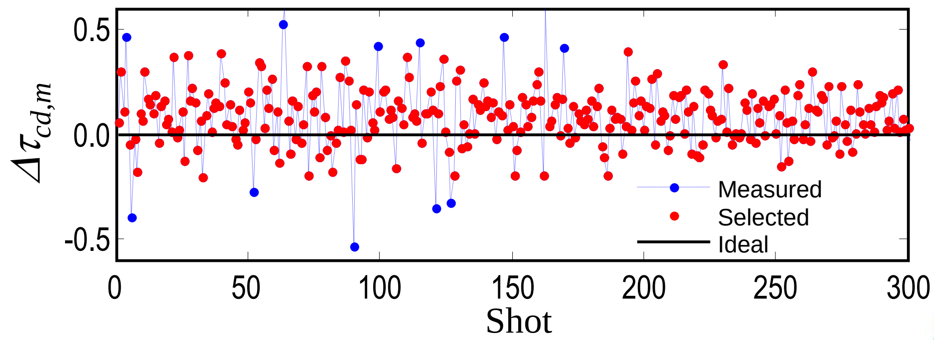


- **IPDA measurements of the CO_2 differential optical depth using Single-Shot and 10 Sec. average**
- **Averaged measurements compared to simulations**
- **Measurements indicated additional systematic bias**

Airborne Testing: Air-Sampling Validation



IPDA CO_2 Differential Optical Depth Measurements Resulted from Off-off-Line Testing.



Off-off-Line Optical Depth Distribution.

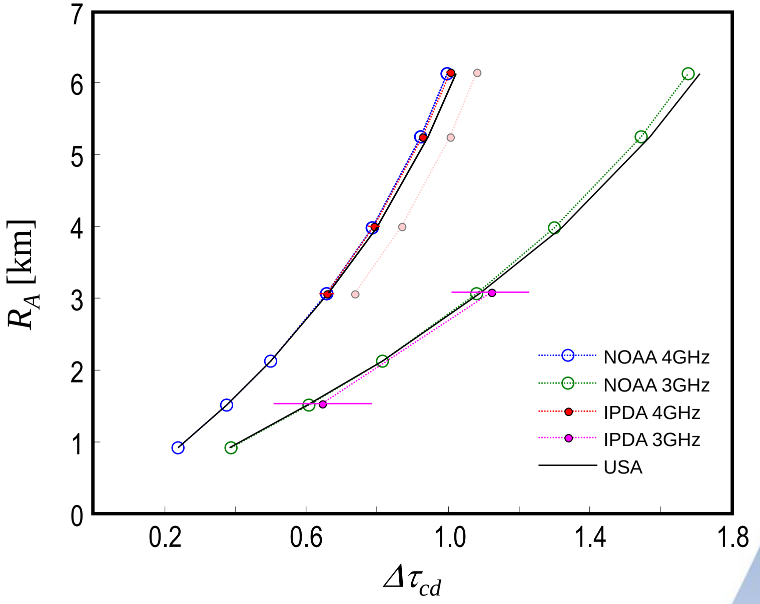
- **Off-off-line Testing for Instrument Systematic Bias Evaluation**
  - **- Precisely known result (zero)**
  - **- Independent on any other instrument**
  - **- Independent on meteorological data**
  - **- Deviation from expected value defines instrument systematic error**
  - **- Noise around expected value define instrument random error**
- **Off-off-line testing conducted during a different flight**

Airborne Testing: Air-Sampling Validation

CO_2 Weighted-Average Column Dry-Air Mixing Ratio Statistical Results and Errors

R_A m	x_{cd} ppm	$X_{cd,c}$ ppm	$X_{cd,m}$ ppm	$\delta X_{cd,m}$ ppm	ΔX_{cd} ppm	Ran. Error	Sys. Error
6125.6	400.75	404.08	405.22	4.15	1.14	1.02%	0.28%
5242.6	400.96	404.34	405.84	4.74	1.50	1.17%	0.37%
3976.7	401.61	404.89	406.60	8.69	1.71	2.14%	0.42%
3051.9	401.55	405.54	407.10	12.83	1.56	3.15%	0.38%

CO_2 Differential Optical Depth Simulation Compared to IPDA Measurements



- **Instrument systematic bias is consistent**
- **Measured off-off-line systematic bias applied to correct other flight result (NOAA)**
- **Averaging of 10 sec (100 shots) applied to reduce random error**
- **CO_2 differential optical depth conversion to CO_2 weighted-average column dry-air volume-mixing**
- **Sensitivity analysis indicated small atmospheric systemic error that correlates to water vapor**

Conclusions

- Airborne 2-μm double-pulse IPDA lidar instrument have been developed at NASA LaRC for atmospheric CO_2 measurements
- Transmitter capability of controlling each pulse independently
- IPDA tuning capability to achieve different weighting functions at different gains
- Double-pulse IPDA ground testing demonstrated successful CO_2 measurement as compared to in-situ sensors
- Double-pulse IPDA CO_2 airborne measurements agrees with different models through different sources
- Off-off-line testing quantifies consistent instrument systematic and random errors and should be applied as a calibration setting
- IPDA airborne CO_2 measurement validation for upto 6km altitude
- Extending IPDA lidar capabilities through triple-pulse operation for simultaneous and independent CO_2 and H_2O measurement